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Template Synthesis of Organic Microtubules

by

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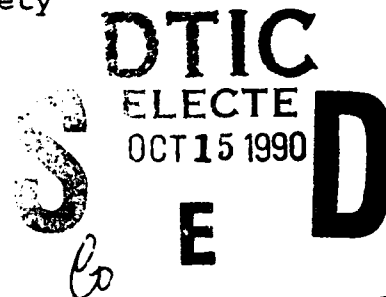
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Organic microtubules,  
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TEMPLATE SYNTHESIS OF ORGANIC MICROTUBULES

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## ABSTRACT

We describe in this report an elegant new method for the synthesis of organic microtubules. This new method is based on the use of a microporous membrane as a template during tubule synthesis. This template method produces tubules with monodisperse lengths and diameters, and length, diameter, and wall thickness can be varied at will. This type of precise control over tubule geometry is not possible with the existing synthetic method. The tubules obtained are composed of chemically and mechanically robust heterocyclic polymers.

Organic microtubules have recently caused a great deal of excitement in the physics, chemistry, and materials science communities (1). Such tubules are inherently intriguing chemical systems, and have myriad proposed technological applications (1); they may also be useful as mimics of biological microtubules (2). The only known synthetic route for preparing organic microtubules (3) involves extremely expensive reagents, and produces tubules with a broad range of diameters and lengths. We have recently discovered a new method for synthesizing organic microtubules. This method uses a microporous membrane as a template during tubule synthesis. The most significant advantage of this template method is that it yields tubules with monodisperse diameters and lengths. We describe this template synthetic method in this correspondence.

The template method entails heterogeneous synthesis of an organic polymer across a microporous membrane. The simplest embodiment of this concept is shown schematically in Figure 1. The template membrane (a Nuclepore polycarbonate filter) contains linear, cylindrical pores of equivalent pore diameter (4). This membrane separates a solution of a monomer from a solution of a polymerization reagent. We have used heterocyclic monomers (e.g. pyrrole) and ferric salts as the polymerization reagent.

The monomer and polymerization reagent diffuse toward each other, through the pores in the template membrane, and react to yield the polymer. We have discovered, however, that the nascent polymer chains adsorb to the pore walls yielding a thin polymer "skin" (5). This "skin" becomes thicker and thicker with time,

until a solid fiber is produced (4a). If polymerization is quenched before this point, polymeric tubules are obtained (5).

A typical synthesis is as follows: Aqueous  $\text{FeCl}_3$  (2 M) and aqueous pyrrole (0.3 M) were added to the outer and inner compartments, respectively, in Figure 1. The membrane used had 0.5  $\mu\text{m}$  pores. Polymerization was allowed to proceed for 25 sec. (The duration of the polymerization period determines the thickness of the wall of the microtubule.) Polymerization was then quenched by rinsing the membrane with water.

Template synthesis can also be conducted electrochemically using membrane-modified electrodes similar to those described in (4b,c). A typical synthesis is as follows: A Nucleopore membrane (1.0  $\mu\text{m}$  pores) was mounted onto the surface of a 0.5  $\text{cm}^2$  Pt disk electrode (4b,c). This electrode was immersed into a  $\text{CH}_3\text{CN}$  solution 0.5 M in N-methylpyrrole and 0.2 M in  $\text{Et}_4\text{NBF}_4$ . Polymerization was accomplished galvanostatically at a current density of 1.0  $\text{mA cm}^{-2}$  (4c); a total of 0.3 coul. of charge were passed.

Both the chemical and electrochemical syntheses yield a collection of polyheterocyclic tubules dispersed within the pores of the template membrane. This configuration would be ideal for some of the proposed applications of organic microtubules (1). The ability to obtain such a parallel array of tubules is a unique advantage of the template method. However, it might also be desirable to free and then collect the tubules. This can be accomplished by dissolving the membrane in  $\text{CH}_2\text{Cl}_2$  and collecting the

tubules by filtration (4c,6).

Figure 2a shows an electron micrograph of typical template-synthesized polypyrrole microtubules. Because the Nuclepore membrane used was 8  $\mu\text{m}$  thick, these tubules are 8  $\mu\text{m}$  long. This ability to produce tubules with monodisperse lengths is a unique and important feature of the template method. Furthermore, because Nuclepore membranes have monodisperse pore diameters (4b), monodisperse tubule diameters are also obtained (Figure 2b). Finally, tubule-diameter and length can be varied, at will, by varying the characteristics of the template membrane (4b).

Figure 2c shows an electron micrograph of electrochemically-synthesized poly(N-methylpyrrole) tubules. Note that while the template membrane has been dissolved away, the tubules are still arranged in an upright array. This is because electrochemically-synthesized tubules are connected at their bases to a thin contiguous film of polyheterocyclic. This ability to produce an upright array of tubules, connected by a common base-layer film, is another unique, and perhaps useful, feature of the template method.

The polyheterocyclic tubules show redox reactions typical of the parent polymer (7) (Figure 3). Thus, like the parent polymer, these tubules can be reversibly switched between electronically insulating and electronically conductive state (7). Furthermore, we have recently shown that template synthesis dramatically enhances the electronic conductivities of such polymers (4a). The redox chemistry in Figure 3 also raises the interesting possibility of making tubule-based electroreleasing systems (8). We are

currently pursuing this possibility.

Finally, it is interesting to speculate on the mechanism responsible for tubule formation in the template process. The key to this process is the adsorption of the nascent polyheterocyclic chain to the pore wall. Heterocyclic polymers are synthesized via oxidation of the monomer and subsequent coupling of the radical cations obtained (7); a cationic polymer is produced. The pore walls in Nuclepore membrane are anionic (9). Thus, electrostatic attraction undoubtedly contributes to the adsorptive interaction between the pore wall and the nascent polyheterocyclic chain. We are using this hypothesis to identify other polymers and membranes which can be used for template syntheses of organic microtubules.

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5. In addition to forming thin polyheterocyclic skins on the pore walls, thin (ca. 0.2  $\mu\text{m}$ ) polyheterocyclic layers are formed on both membrane faces. These layers must be removed before dissolution of the template membrane. This can be accomplished by rubbing with a Kim-Wipe.
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- Figure 1. Schematic of apparatus used to conduct chemical template synthesis of organic microtubules.
- Figure 2. Scanning electron micrographs of chemically-synthesized polypyrrole microtubules (a,b) and electrochemically-synthesized poly(N-methylpyrrole) microtubules (c).
- Figure 3. Cyclic voltammogram of an array of poly(N-methylpyrrole) microtubules (see Figure 2c). Tubule diameter was  $1.0\text{ }\mu\text{m}$ . Substrate electrode was  $0.5\text{ cm}^2$  Pt disk. Supporting electrolyte was  $0.2\text{ M Et}_4\text{NBF}_4$  in  $\text{CH}_3\text{CN}$ . Scan rate was  $10\text{ mV s}^{-1}$ . Anodic currents are down and cathodic currents are up in this figure.

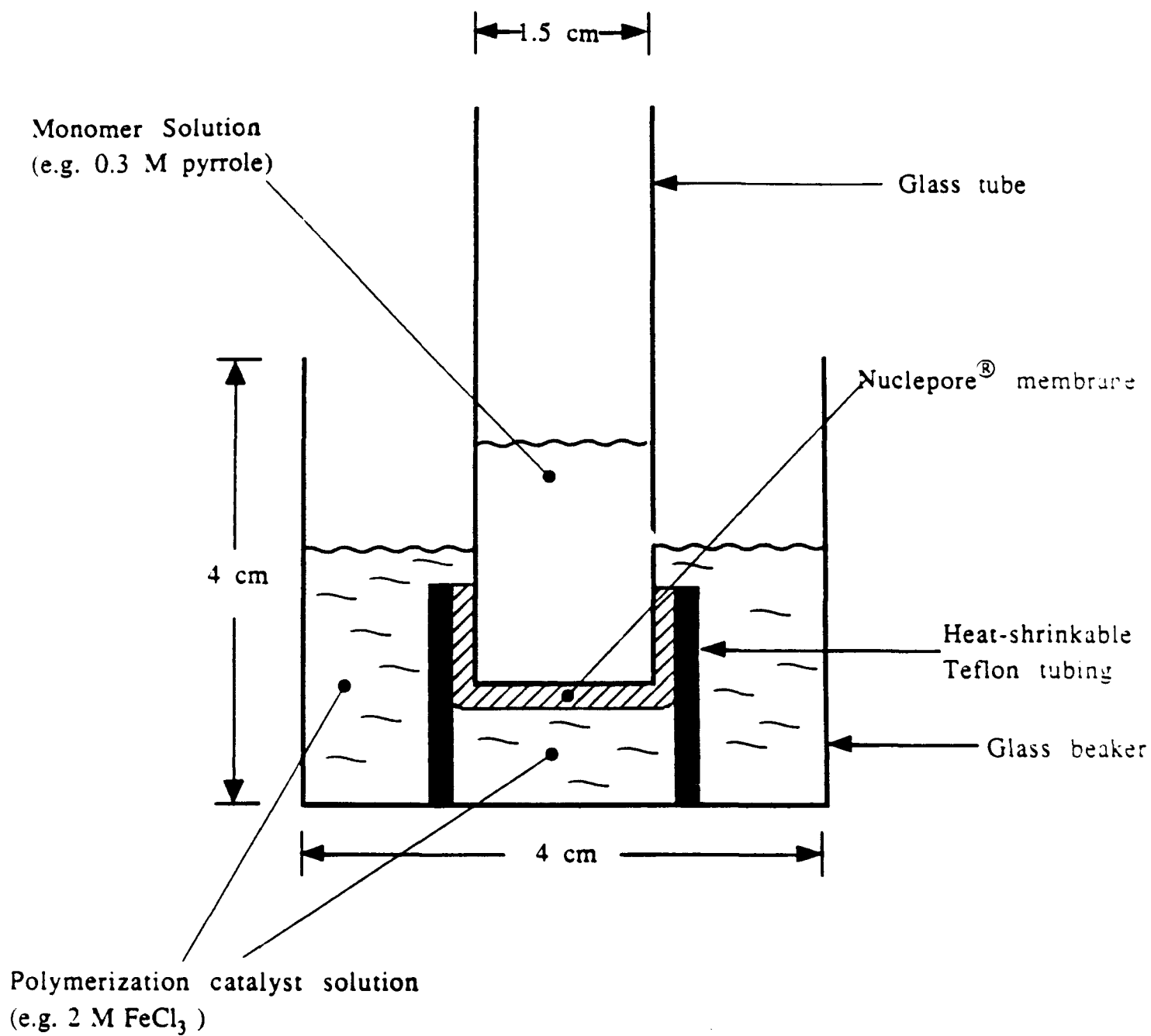
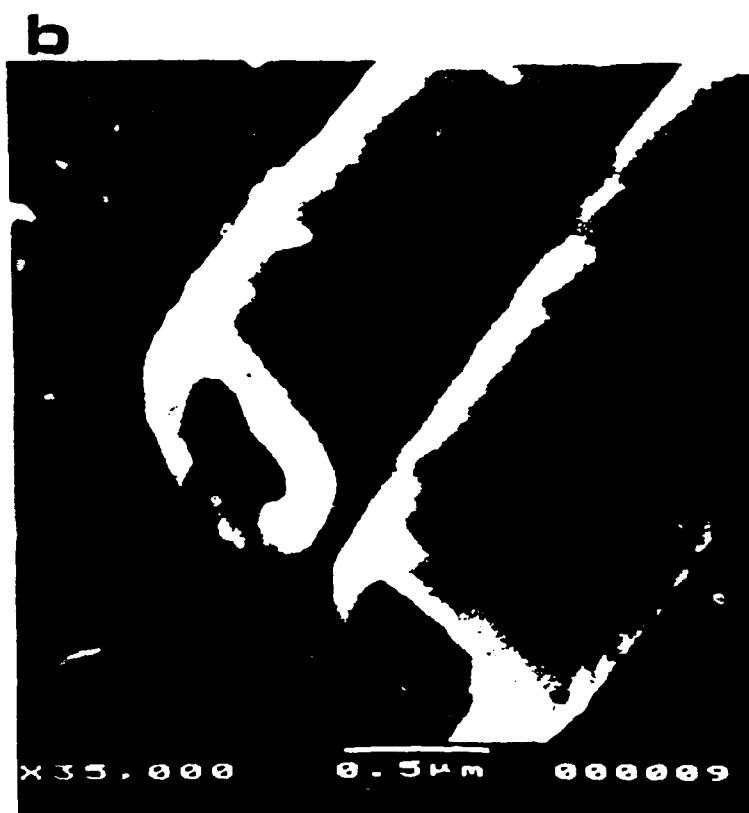


Fig. 1



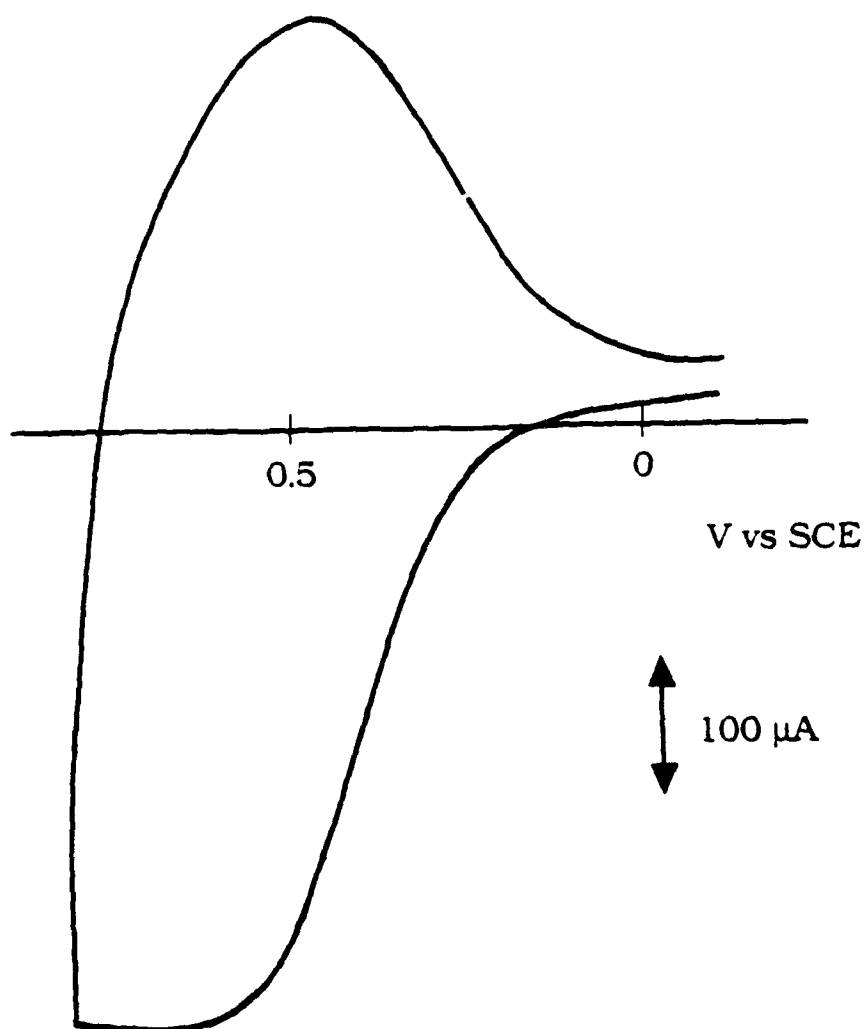


Fig. 3